Ship Detection with Short Coherent Integration Time in Over-the-Horizon Radar

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Abstract — **To realize the ship detection with short coherent integration time (CIT) is an operational requirement for skywave over-the-horizon radar (OTHR). However, short CIT and the resulting low Doppler resolution cannot separate the ship from the close powerful ocean clutter. To resolve this problem, Fourier transform based clutter cancellation is proposed as well as some super-resolution spectral estimation techniques. In this paper, we still use clutter subtraction scheme but the clutter parameter estimation is improved by analyzing the Fourier phase information. As the result, the estimation accuracy is enhanced and better cancellation performance may be achieved, which to some extent will decrease the power and spreading of clutter residue and benefit the ship visibility and identification.**

I. INTRODUCTION

The skywave over-the-horizon radar (OTHR) is unique in radar family that employs the ionosphere to refract the radar high frequency signal (3-30MHz) to illuminate the target from the top down, thus significantly extending the detection range of 1000-4000km and permitting wide-area surveillance. However, scanning such vast coverage area requires relatively short coherent integration time (CIT) to increase the data rate, so as to ensure the work of the tracker.

For aircraft, short CIT is not a problem since their speeds separate them well from the ocean/ground clutter. But for ships, the low Doppler resolution resulting from the short CIT is not sufficient in most case to distinguish them from the close powerful ocean clutter.

In order to improve the signal-to-clutter ratio (SCR), a Fourier transform based clutter cancellation algorithm is proposed by Root [1-2]. By modeling the first-order clutter as sinusoid and subtracting it from the data, the ships can be exposed in short-time Doppler spectrum. This clutter subtraction means that the amplitude, frequency and initial phase of clutter must be estimated. In [1-2], Fourier based techniques is utilized to estimate the clutter, in which the clutter frequency and amplitude are directly obtained by the peak in Doppler spectrum, and initial phase is found by numerical search in the range $0-2\pi$ that minimize the energy of estimation error. However, since the Doppler resolution of short-time data is low, the clutter frequency estimation is not accurate if only maximal Fourier transform amplitude is used. This imperfect parameter estimation and clutter subtraction will result in the clutter residue. To remove them, iteration cancellation technique is used until the ships are shown up. However, as algorithm proceeds by iteration, the clutter residue will spread in Doppler spectrum and present a difficulty in ship identification and even masks the ships.

In this paper, an improvement to above Fourier based clutter cancellation is presented. We employ high-accuracy parameter estimation method [3] to obtain the clutter parameters, while the basic clutter subtraction and iteration cancellation is the same as in [1-2]. In this method, not only the amplitude information of dominant peak in Fourier spectrum but also the phase information is considered. With Fourier phase analysis, better clutter frequency and amplitude estimation can be achieved. As the result, after clutter cancellation, the clutter residue may have lower power and lesser spreading in Doppler spectrum, which will benefit the ship identification. Besides, in this method, the initial phase of the clutter can be directly calculated, avoiding the numerical search in the range $0-2\pi$.

II. CHARACTERISTICS OF OTHR OCEAN CLUTTER

Fig.1 shows a typical Doppler spectrum of ocean echoes in high-frequency band. The dominant features of this spectrum are the two sharp peaks that usually called first-order Bragg peaks, which arise from the resonant scattering of the ocean waves having a wavelength that is one-half of the radar wavelength and the resonant scattering is much powerful than other echoes. The Doppler frequencies of the Bragg peaks are $\pm 0.102\sqrt{f_0}$ (Hz), where f_0 is the radar operating frequency in MHz, and the sign $\pm$ indicates resonate ocean waves is advancing towards the radar or receding from it.

Since in the Doppler spectrum, the first-order Bragg peaks are the dominant component of the ocean echoes, the time domain data sample of the ocean clutter is approximate to sinusoidal signal which provides the theoretical foundation for ocean clutter cancellation based on sinusoidal model.

However, some ionospheric factors will corrupt the radar signal [4-5]. The ionospheric phase path variation is one of

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them, which will impose a phase disturbance on the echo signal and make the sinusoidal clutter model is not valid. Fortunately, for short time series, this contamination is in lower level. But ionospheric multimode propagation presents more difficulties. When multimode propagation exists, more than two Bragg peaks may appear in the Doppler spectrum, and the extra Bragg peak may be mistakenly regarded as the ship. Besides, due to the low Doppler resolution, the multiple positive (or negative) Bragg line may locate in one broad peak, which will affect the clutter parameter estimation and further influence clutter cancellation.

III. BASIC CLUTTER CANCELLATION ALGORITHM

For OTHR ship detection with short CIT, presently at least two schemes have been proposed to overcome the resolution loss. One is directly employing the super-resolution spectral estimator instead of the Discrete Fourier Transform (DFT) to obtain the Doppler information [6-8]. The other is firstly suppressing the strong ocean clutter, thus DFT can still extract the ship target from the short-time series.

Though directly using filter in Doppler spectrum can cancel the ocean clutter, it also possibly destroys or even filters out the neighboring ship since the mainlobe of ocean clutter is broad in short-time Doppler spectrum. As the dominant component of ocean clutter (i.e., the first-order Bragg peak) can be considered as sinusoidal signal in time domain, Root proposed to cancel the ocean clutter by subtracting the sinusoid from the time series [1-2]. This action unlikely affects the ship component but requires to estimate the frequency, amplitude and initial phase of the sinusoid that represents the ocean clutter.

In Root's scheme, the amplitude A and frequency f of the sinusoid are estimated directly from the clutter peak in Fourier spectrum, while the initial phase is estimated by the minimizing the energy of the error between the model sinusoid and the real data, just as indicated in equation (1).

$$\varepsilon(\phi)=\sum_{n=1}^{N}\left|x(n)-Ae^{j\phi}e^{j2\pi f(n-1)\Delta T}\right|^{2} \tag{1}$$

where $x(n), n=1,\cdots N$ is the time domain data sample in a CIT for a given range-azimuth cell; ΔT is the sampling interval; ϕ is the initial phase of the model sinusoid, which is obtained through the numerical search in the range of $0-2\pi$ by minimizing the energy of the error. When the dominant clutter peak has been estimated and subtracted, other clutter peak will remain as well as the clutter residue due to the imperfect clutter parameter estimation and cancellation. Then this estimating and subtracting is repeated to the dominant remaining peaks until the ocean clutter is suppressed and the ship is shown up.

At each iteration, only the largest remaining peak is estimated and subtracted. Generally this estimation has some error, resulting in the clutter residue. Fortunately, this clutter residue can also be approximately modeled as sinusoid [1] and they will be canceled at further iteration. However, as algorithm proceeds by iteration, the estimation error will accumulate and the clutter residue will spread in Doppler spectrum away from the original Bragg peaks. The spreading of clutter residue may make the identification of ship from the clutter peak more difficult and complicate the program of automatic search and identification of ships. To avoid mistakenly regarding the ship as the clutter residue and then canceling it, clutter margin or Doppler frequency is used as a criterion in [1-2] to demarcate the clutter and ship. But if the spreading of clutter residue is severe or the ship is close to the clutter residue, the erroneous ship identification may occur. Besides, sometimes after clutter cancellation of several iterations the ship is still masked by the clutter residue, and to find the ship non-coherent integration of power over time may be required.

If better clutter cancellation at each iteration can be achieved, the power and spreading of clutter residue may reduce. This will benefit the visibility and identification of ships. However, better clutter cancellation means that better clutter parameter estimation should be achieved. For the case of a multiple sinusoid model, the frequency estimation is the key. But for short time series, direct Fourier transform rarely gives accurate frequency estimation. The super-resolution spectral estimator can provide better frequency resolution and more accurate frequency estimation, but it highly depends on the similarity of the assumed model to the data. In this paper, we introduce a high-accuracy sinusoid parameter estimation method [3] to OTHR ship detection with short CIT. It not only uses Fourier amplitude information but also Fourier phase information to get the clutter parameter, thereby enhancing the clutter estimation and cancellation performance.

IV. CLUTTER CANCELLATION USING HIGH-ACCURACY PARAMETER ESTIMATION

For a sinusoidal signal $s(t)=a\exp[j(2\pi f_0 t+\phi_0)]$ with the amplitude a, frequency f_0, initial phase ϕ_0, and duration T, its N-point discrete Fourier spectrum is $S(k)=A\exp(j\varphi)$. When the amplitude of $S(k)$ reaches its maximum A_m, the amplitude term and corresponding phase term of $S(k)$ is

$$A_m=\frac{a\sin[\pi(f_0T-k_0)]}{\sin[\pi(f_0T-k_0)/N]} \tag{2}$$

$$\varphi_m=\phi_0+(1-1/N)(f_0T-k_0)\pi \tag{3}$$

where A_m and φ_m can be called Fourier amplitude information and Fourier phase information, respectively.

Previously we only use the maximal Fourier amplitude A_m to estimate the signal frequency $\hat{f}_0=k_0/T$. But due to the "picket-fence" effect of sampling, the genuine frequency of the signal often locates between the two discrete frequencies, especially for the short time series that has low frequency resolution and large frequencies separation between the neighboring two discrete points. Hence for short-time data, the frequency estimation error may be large if only Fourier amplitude information is used.

Here, we combine the Fourier phase information to estimate the sinusoidal frequency. In (3), φ_m and k_0 can be directly obtained from FFT (Fast Fourier Transform), but

since the initial phase ϕ_0 is unknown, it is unable to get the genuine frequency f_0. To overcome this problem, we divide the time samples into two parts, the former $N/2$ points and the latter $N/2$ points, and then perform FFT respectively. Thus the Fourier phase difference is $\varphi_2 - \varphi_1 = 2\pi f_0 \cdot \frac{T}{2} = \pi f_0 T$, where φ_1, φ_2 is the Fourier phase information of the largest peak in the former and the latter $N/2$-point Fourier spectrum, respectively. Due to the 2π ambiguity of the phase, the actual measured phase difference is $(\varphi_2 - \varphi_1)_{measure} = \pi f_0 T - 2\pi k_{01}$, where k_{01} is the discrete point corresponding to the maximal amplitude in the $N/2$-point Fourier spectrum. Thus the error between the genuine frequency f_0 and the coarsely estimated frequency $\hat{f}_0$ is

$$(\varphi_2 - \varphi_1)_{measure} = \pi T(f_0 - 2k_{01}/T) = \pi T \Delta f$$
$$\Rightarrow \quad \Delta f = \frac{(\varphi_2 - \varphi_1)_{measure}}{\pi T} \tag{4}$$

The variation range of Δf should be $-0.5 f_{reso} \sim 0.5 f_{reso}$, where f_{reso} is the frequency resolution equal to $1/T$. If Δf is out of the above variation range due to the computation of 2π ambiguity of phase, it is corrected as follows,

$$\begin{aligned} &\text{when} \quad \Delta f > 0.5 f_{reso} \; , \; \Delta f = \Delta f - f_{reso} \\ &\text{when} \quad \Delta f < -0.5 f_{reso}, \; \Delta f = \Delta f + f_{reso} \end{aligned} \tag{5}$$

Thus the genuine frequency of the signal is $f_0 = \hat{f}_0 + \Delta f$. Based on this estimated frequency f_0, and A_m , φ_m that have been obtained by FFT, the signal amplitude a and initial phase ϕ_0 can be directly calculated through the equation (2) and (3). This eliminates the numerical search for initial phase in the range $0-2\pi$. For details about Fourier phase analysis method, see [3].

Next we present the summarized processing step of this method:

1) Firstly perform discrete Fourier transform of N -point data, and get the Fourier amplitude information A_m and phase information φ_m as well as the coarsely estimated frequency $\hat{f}_0$.

2) Divide the data into two parts and perform discrete Fourier transform respectively. Estimate the difference of the Fourier phase information $(\varphi_2 - \varphi_1)_{measure}$ between the two parts, and get the frequency error Δf based on equation (4) and (5). Thus the genuine frequency is $f_0 = \hat{f}_0 + \Delta f$.

3) Rewritten the equation (2) and (3) as

$$A_m = \frac{a \sin[\pi \Delta f T]}{\sin[\pi \Delta f T / N]}$$
$$\varphi_m = \phi_0 + (1 - 1/N)\Delta f T \pi$$

since Δf , A_m and φ_m has been obtained, the signal amplitude a and initial phase ϕ_0 can be directly calculated.

This approach has utilized the Fourier phase information to estimate signal frequency, it generally requires the Bragg peaks have high clutter-to-noise ratio. This requirement is usually satisfied in OTHR. In this approach, the frequency estimation is calculated in two steps, first gives the coarse estimation, and then improves by Fourier phase analysis. Once the frequency is given, the amplitude and initial phase in this method is directly calculated, which eliminated the numerical search for initial phase in the range $0-2\pi$. In clutter cancellation, the frequency and initial phase estimation are important. The erroneous frequency and initial phase estimation will increase the iteration number and make the spreading the clutter residue more serious, as we will see in the processing result.

V. THE PROCESSING RESULTS

Fig.2 shows the Doppler spectrum of OTHR data operating at 7.5MHz with coherent integration time 44s (64-point data), backscattered from the ocean surface. In these data, a ship peak is present at the Doppler frequency -0.45 Hz. Now we extract the first 16-point data from Fig. 2, and its Doppler spectrum is shown in Fig.3, which is obtained by direct 16-point FFT. Due to the decrease of Doppler resolution, in this figure the ship peak is not visible. In the following, the basic ocean clutter cancellation approach and our improvement of enhancing the parameter estimation accuracy are applied to these data, and the processing results are compared.

In the basic ocean clutter cancellation, the clutter frequency and amplitude are directly estimated from the peak in the Fourier spectrum. And the initial phase is found by numerical search. However, for the 16-point Doppler spectrum shown in Fig.3, the error of frequency estimation may be large due to severe “picket-fence” effect, which will further influence the initial phase estimation and lead unsatisfactory results. In order to enhance the estimation accuracy and thereby get better cancellation performance, the simplest method is to employ time domain zero-complemented FFT to estimate the clutter parameters. Though this action cannot improve the Doppler resolution, it increases the frequency point in the Doppler observation range, thereby enhancing the frequency estimation accuracy.

Fig.4 shows the zero-complemented 128-point Doppler spectrum of original 16-point data. Fig.5 and 6 shows the spectrum after clutter cancellation by 2nd-iterations. In Fig.5, the frequency and amplitude of the ocean clutter are obtained directly from 16-point Doppler spectrum while in Fig.6 they are estimated by zero-complemented 128-point Doppler spectrum. In Fig.5, due to the bad frequency estimation and the resulting bad initial phase estimation, the ship peak is still masked by the clutter residue, and to find it, more iteration is required. However, increasing iteration will also increase the spreading of the clutter residue and present the difficulty in ship identification. Compared with Fig.5, the cancellation performance is increased significantly in Fig.6 and the ship has been shown up. But to identify the ship from the clutter residue, the criterion of Doppler frequency is required. Besides, zero-complemented FFT is still affected by “picket-fence” effect.

Fig.7 presents the Doppler spectrum after 2nd-iteration cancellation in which the clutter parameters are estimated by Fourier phase analysis method. Compared with Fig.5 and 6,

in this figure the ship peak appears, meanwhile the power and spreading of clutter residue is reduced due to the high parameter estimation accuracy and better clutter cancellation. This will benefit the visibility and identification of ships and be helpful for automatic detection of program. In addition, using FFT phase analysis can directly get the initial phase estimation. This eliminates the need of numerical search in the range of $0-2\pi$.

VI. CONCLUSION

Realizing ship detection with short CIT will enhance the OTHR data rate and guarantee the timely surveillance of the large areas. But the short CIT and the resulting low Doppler resolution cannot separate the ships from the close powerful ocean clutter. To overcome this problem, the ocean clutter cancellation algorithm is proposed by Root. In this paper, some improvement is presented. By combining the Fourier phase information, better clutter parameter estimation can be achieved. As the result, after clutter cancellation, the power and spreading of clutter residue in Doppler spectrum may reduce, which is helpful for the visibility and identification of ships. In addition, this method can directly get the initial phase, which eliminated the numerical search in the range $0-2\pi$. However, note that this approach employs the phase information, it generally requires the Bragg peaks have high clutter-to-noise ratio. This requirement is usually satisfied in OTHR.

Finally, we would point out that the multimode propagation is a limitation for ship detection. First, it yields more than two Bragg peaks and the extra Bragg peak may be mistakenly regarded as the ship target. Second, the multiple positive (or negative) Bragg lines may be very close in Doppler spectrum and have approximate power, thus the Fourier phase analysis method may not get correct parameter estimation and lead the clutter cancellation unsatisfactory. Though selecting proper radar operating frequency can achieve single mode propagation, this is not always feasible due to the ionospheric condition and the desired surveillance region. Therefore, it requires further research to remove this contamination before ship detection.

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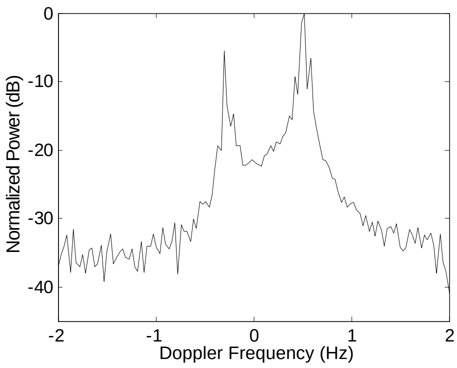

Fig.1 The Doppler spectrum of ocean echoes in high-frequency band

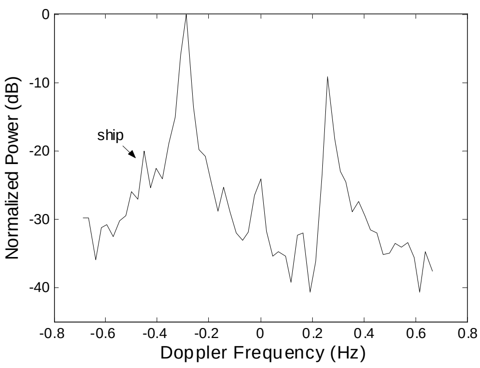

Fig.2 The Doppler spectrum of 64-point data

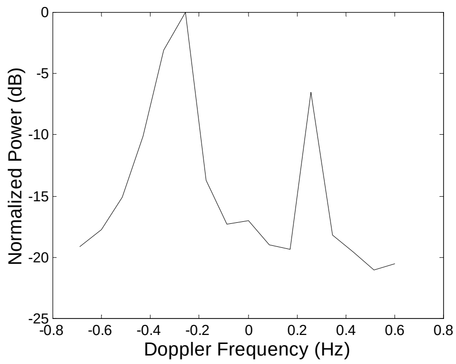

Fig.3 The Doppler spectrum of the first 16-point data extracted from Fig.2

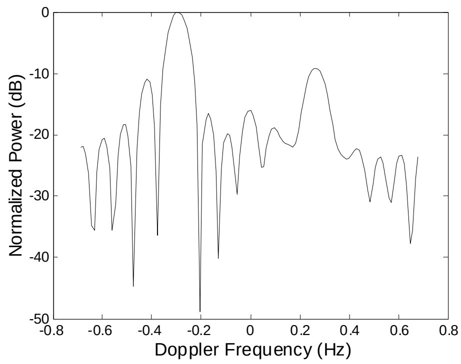

Fig.4 The zero-complemented 128-point spectrum of 16-point data

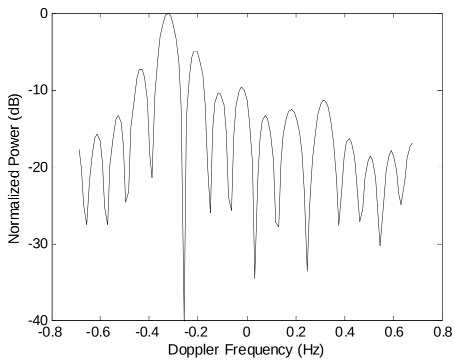

Fig.5 The spectrum after clutter cancellation by 2nd-iterations where the clutter parameters are estimated by 16-point FFT

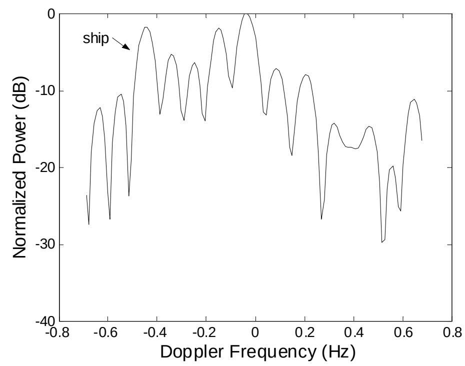

Fig.6 Still after 2nd-iteration cancellation, but the parameters are estimated by zero-complemented 128-point FFT

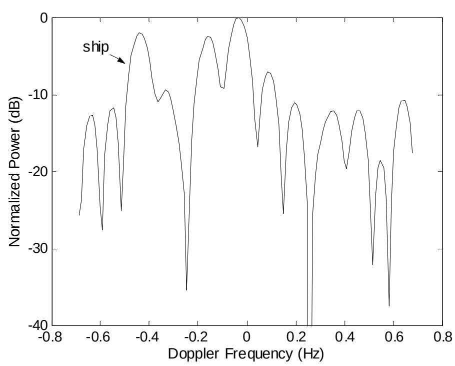

Fig.7 Still after 2nd-iteration cancellation, where the clutter parameters are estimated by Fourier phase analysis method